# Transient simulation of LBE cooled CHTR under natural circulation with 3D multi-physics code ARCH-TH

D. K. Dwivedi
*Bhaba Atomic Research Center*, ddwivedi@barc.gov.in

Anurag Gupta
*Bhaba Atomic Research Center*

Umasankari Kannan
*Bhaba Atomic Research Center*

**Transient simulation of LBE cooled CHTR under natural circulation with 3D multi-physics code ARCH-TH**

D.K. Dwivedi,*† Anurag Gupta*† and Umasankari Kannan*†

** Reactor Physics Design Division, Bhabha Atomic Research Centre, Mumbai, India*
*†Homi Bhabha National Institute, Anushakti Nagar, Mumbai-400094, India*
*Email: ddwivedi@barc.gov.in*

## INTRODUCTION

Compact High Temperature Reactor (CHTR) is envisaged as technology demonstrator for Indian comprehensive programme for high temperature process heat applications of nuclear energy such as thermo-chemical splitting of water for hydrogen production [1-3]. The 100 kWth CHTR is being designed as thorium based TRISO fuelled, beryllium oxide moderated and lead-bismuth eutectic (LBE) cooled prismatic block type vertical reactor [4]. The core outlet temperature is designed to be 1000°C at nominal power. The major core design parameters of CHTR are given in TABLE I. The core consists of twelve control rods in outer channels for power regulation and two independent shutdown systems for protection. The conceptual design has several passive safety features such as negative temperature coefficients of reactivity, core heat removal through natural circulation of LBE coolant during normal operation, rejection of entire heat through heat pipes to the atmosphere under accidental conditions etc. The tri-structural isotropic (TRISO) fuel particles are being used in CHTR for better fuel integrity and safety limits at high temperature operation with deep burnup. The cross-sectional view of CHTR core is shown in Fig.1.

The high temperature core configuration of prototype CHTR requires multi-physics multi-scale modeling based tools for investigating the normal operational behavior as well as anticipated transients. In view of that, the indigenous 3D space-time neutronics code ARCH is being integrated with thermal-hydraulic capability for feedbacks and referred as ARCH-TH [5-7]. The predictions of the code are validated with several benchmark problems. In our earlier study, the ATWS in operating condition of CHTR was investigated with given average inlet coolant mass flow rate in the channels with temperature feedbacks [8]. The code ARCH-TH has been advanced with capability to simulate the natural circulation phenomenon of LBE coolant in coupled parallel multi-channel of CHTR under various operating and transient conditions. The code can simulate the close loop coolant dynamics by solving the mass, energy and momentum conservation equations in all the channels which are connected at upper & lower plenum only (Fig.2).

The steady state operations as well as unprotected transient of control rod withdrawal at full power of CHTR during initial life cycle have been investigated with code ARCH-TH. The study has been carried out with phenomena of natural circulation of LBE coolant in coupled parallel multi-channel in the core. The analyses and results are discussed in the next section.

TABLE I. Major core design parameters of CHTR

| Attributes | Values |
|---|---|
| Reactor power | 100 kWth |
| Fuel | $^{233}$U-Th in TRISO particles |
| Fuel channels/ pitch | 19/13.5 cm |
| Core life cycle | 15 effective FPYs |
| Moderator/ Reflector | BeO/ BeO and Graphite |
| Coolant | Lead Bismuth Eutectic |
| Coolant inlet/outlet temp. | 900°C/ 1000°C |
| Core height/diameter | 100 cm/ 127 cm |
| Axial reflector thickness | 15 cm top and bottom |
| Core mass flow rate | 6.7 kg/s |
| Power regulation | 12 rods of Ta alloy |
| Primary SDS | 6 shut-off rods |
| Secondary SDS | 12 movable BeO blocks |
| Reactivity Coefficient (Fuel, Moderator and Coolant Temperature) | $-5.6\times10^{-6}$ , $-1.8\times10^{-5}$ and $-0.38\times10^{-6}$ in k/°C respectively |

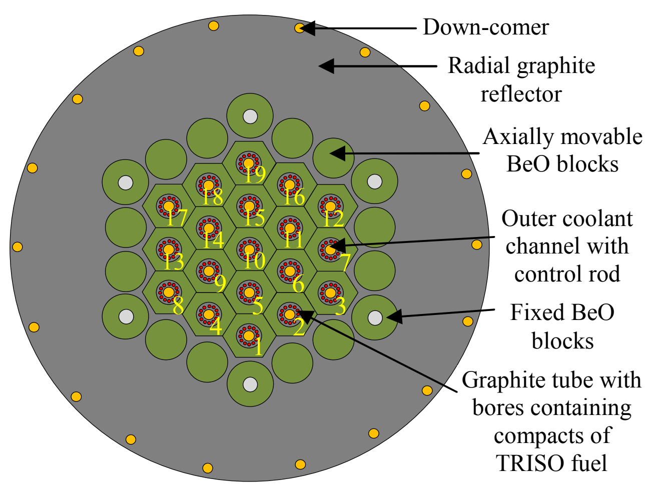


Fig.1. Schematic of core cross-sectional view of CHTR depicting channel numbers

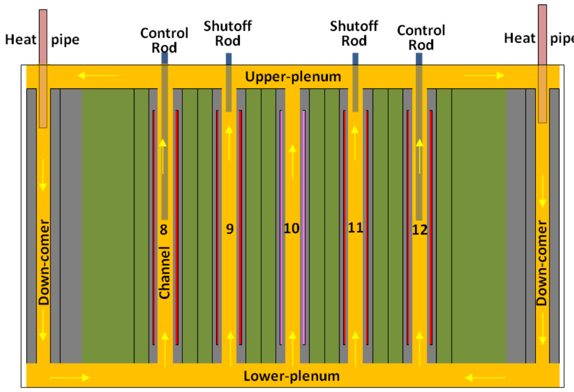


Fig.2. Axial schematic of CHTR with channels connected at lower and upper plenum

## RESULTS AND ANALYSES

In conceptual design of CHTR [4, 8], the core consists of 19 prismatic beryllium oxide moderator blocks each containing centrally located graphite tubes (Fig.1). Each tube carries 12 equi-spaced longitudinal bores of 1 cm diameter and 70 cm active length. These bores are filled with fuel compacts made of TRISO coated particles embedded in graphite matrix. The TRISO coated particles are in the form of microspheres of ($^{233}$U -Th) carbide kernel coated with three layers of soft pyrolitic carbon, SiC and a hard outer carbon layer. Gadolinium as burnable poison is also mixed in kernel of the TRISO particles in central fuel assembly. The liquid metal (Pb-Bi eutectic) coolant flows by natural circulation between the lower and upper plenum, upward through the fuel tubes and returning through eighteen down-comers. The average inlet and outlet coolant temperature are 900$^{o}$C and 1000$^{o}$C respectively. The core average coolant mass flow rate is about 6.7 kg/s at full power. The core heat is transferred to secondary side by means of high temperature heat pipes inserted in down comers at upper plenum [9].

3D multi-physics code ARCH-TH is based on finite difference method with efficient IQS module for reactor kinetics. The code is integrated with TH capability based on 1D-radial heat conduction in multi-channel and close loop coolant dynamics in coupled parallel channels for temperature feedbacks [7, 8]. Here, all the channels can have different power as well as thermo hydraulic conditions. All 19 channels in CHTR are coupled through equal pressure drop criteria for natural circulation as they have common upper and lower plenums. In the analysis, 18 down-comers (DC) in the design are assumed with similar thermo-physical conditions. The outlet coolant is supposed to be losing heat through heat pipes as primary heat exchangers and rest of the down-comers length have adiabatic flow regions. The ideal behavior of primary heat exchanger is assumed for present study so that the coolant inlet temperature is at 900$^{o}$C during normal operation as well as transients. For low Prandtl number fluid flow of LBE coolant in CHTR, Chen and Tak correlation has been used for heat transfer coefficients [10]. The temperature dependent thermo-physical properties of LBE coolant at different time steps are taken from OECD/NEA Nuclear Science Committee, 2007 [11]. The correlations to compute form and frictional losses of coolant flow in the loop are taken from OECD/NEA, Handbook on LBE, 2015 [12].

## Steady state operation of CHTR

The code ARCH-TH is utilized to simulate the steady state operation of CHTR with natural circulation coolant in the channels. The core is being operated at 100kWth with 900$^{o}$C inlet at nominal power. It is considered that about 91.4% of thermal heat generated through fission is being taken out by coolant flowing in the channels. The thermal power, mass flow rate as well as outlet temperature of various channels in CHTR during nominal operation are predicted in natural circulation condition and are shown as in Fig.3.

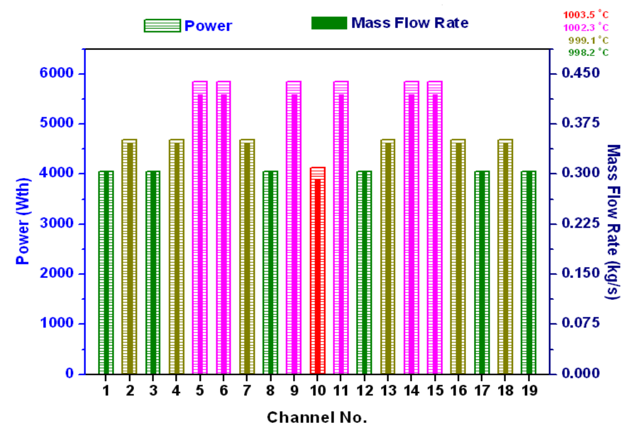


Fig.3. Thermal power, mass flow rate and outlet temperature of channels in CHTR during full power operation

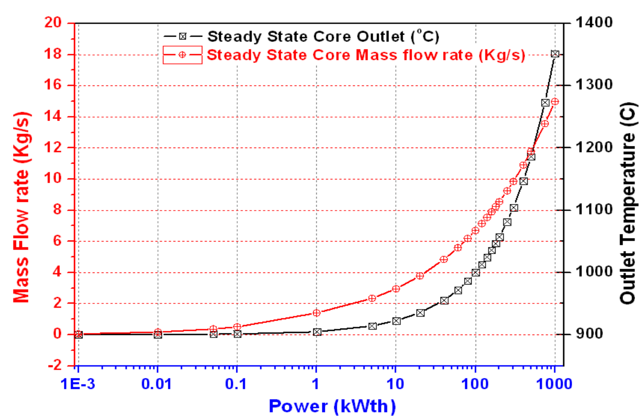


Fig.4: Predicted steady state core average mass flow rate and outlet coolant temperature at different power level in natural circulation condition with code ARCH-TH

In the present design of coolant circuit of parallel multi-channel in CHTR with 18 down-comers, the core average mass flow rate and outlet temperatures are also estimated at various core power from 1Wth to 1MWth as shown in Fig.4. Here inlet temperature is taken at 900°C.

## Control rod withdrawal transient in CHTR

The unprotected withdrawal of control rod transient in CHTR has been assessed at full power. The study has been carried out with code ARCH-TH with natural circulation of coolant in the core. The transient is assumed to be initiating with withdrawal of single control rod of worth 1.04 mk in 2.3 second [8]. It is assumed that shutdown systems are not being activated for trip. The rising power as well as temperature in the core is being arrested with reactivity feedbacks from change in temperature of fuel, moderator and LBE coolant. The transient has been followed up to 1800 second. The core power, coolant enthalpy, reactivity, channel pressure drop as well as peak fuel, moderator and outlet temperature during transient have been predicted and are presented in Fig. 5 to Fig.8.

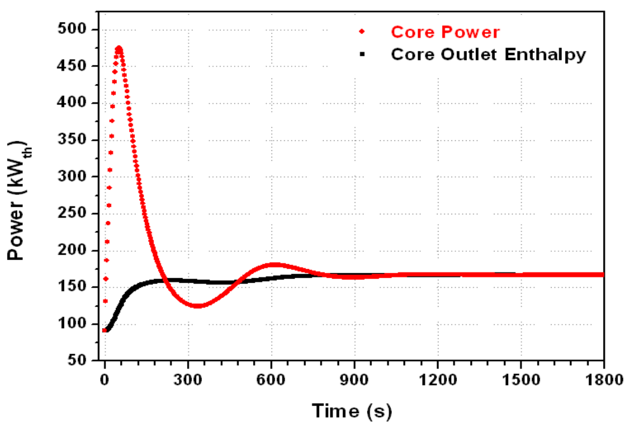


Fig.5. Variation of thermal power and change in coolant outlet enthalpy during transient

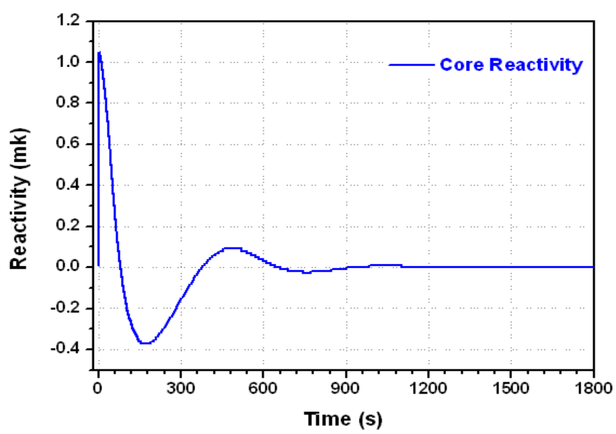


Fig.6. Variation of net reactivity in the core during transient

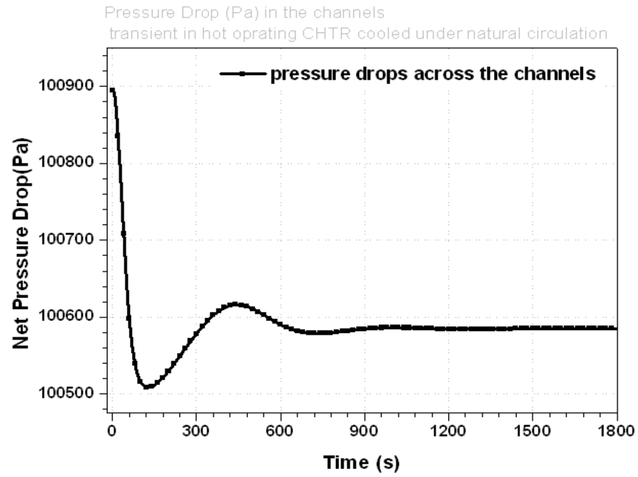


Fig.7. Variation of pressure drop across the channels during transient

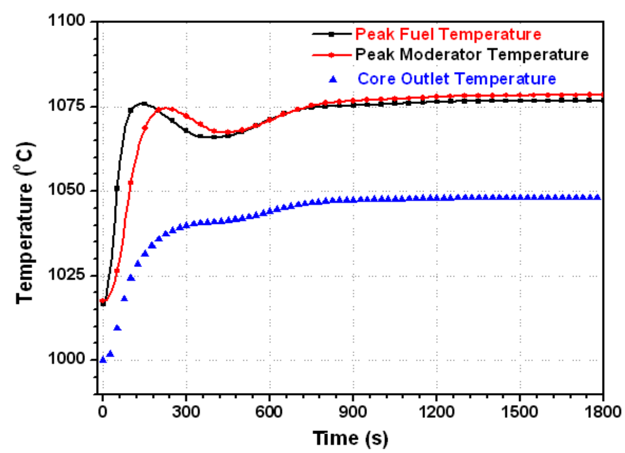


Fig.8. Variation of peak fuel, moderator and coolant channel outlet temperature during transient

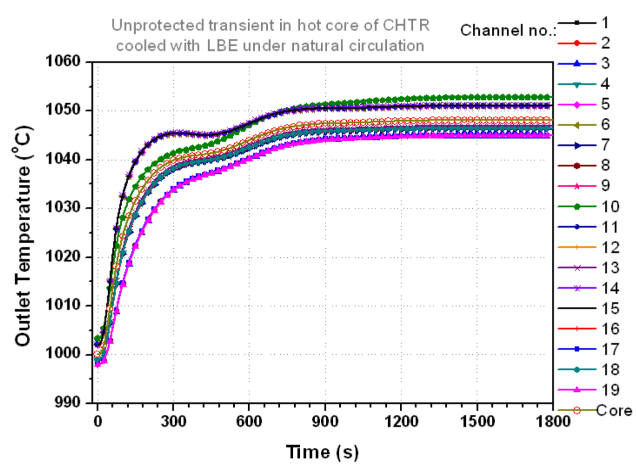


Fig.9. Variation of outlet coolant temperature of the channels during transient

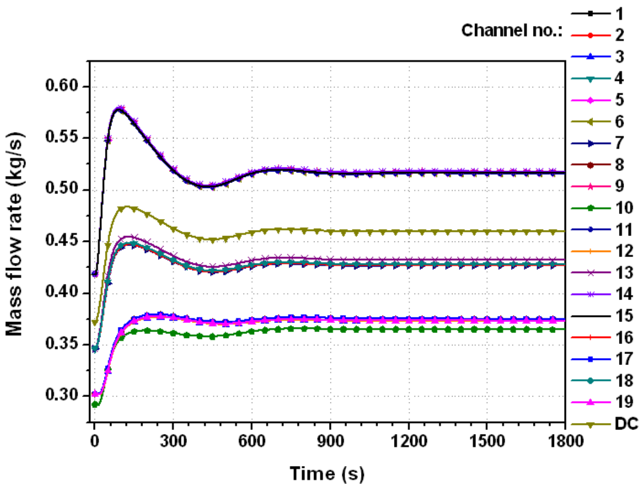

Fig.10. Variation of coolant mass flow rate in the channels during transient

The variation in coolant outlet temperature and mass flow rate in all the channels of CHTR during transient are shown in Fig. 9 and Fig.10 respectively.

The core power is found to be initially rising to about 5 times in 52 s (Fig.5) and then reducing and stabilizing at about 1.8 times of its initial value due to negative temperature feedbacks from fuel and moderator (Fig.6). The total core mass flow rate is finally stabilizes to 1.24 times of initial value with average outlet temperature 1048$^{o}$C (Fig.8 and 9). It is inferred that the peak fuel temperature is far below the safety limits of 1600$^{o}$C for TRISO fuel in the core during transient. It has also been observed that the core mass flow rate increases during over power transient in natural circulation condition (Fig.10) resulting to lesser rise in temperature in the channels (Fig.9).

## CONCLUSION

The envisaged core of Compact High Temperature Reactor was investigated for unprotected transient of inadvertent withdrawal of control rod. The study has been performed with indigenous 3D multi-physics code ARCH-TH. The TH capability in the code has been successfully augmented for modeling natural circulation of liquid metal coolant in high temperature system. The steady state of the core was analyzed to predict the channel mass flow rate and outlet temperatures at full power during initial life cycle. The core was also simulated to predict the key parameters defining neutronics as well as thermal-hydraulics during transient. The peak temperatures of fuel and coolant outlet were found to well within the safety limits even in unprotected condition. The negative temperature feedbacks from fuel and moderator were found to be very effective to arrest the rise of transient power in CHTR. It was also observed that the core is stabilizing at higher power with increased flow rate for heat removal under natural circulation condition of coolant. The study of several safety transients in CHTR like loss of heat sink accident are being considered as future work. The code is also being augmented for the study.

## REFERENCES

1. R.K. Sinha, “Advanced nuclear reactor systems – an Indian perspective” *Energy Procedia*, **7**, pp. 34-50, (2011)
2. R.K. Sinha et al., “Generation IV concepts: India”, *Handbook of Generation IV Nuclear Reactors*, Woodhead Publishing Series in Energy, pp. 413-452, (2016)
3. I.V. Dulera et al., “High temperature reactor technology development in India”, *Progress in Nuclear Energy* **101**, 82-99 (2017)
4. D.K. Dwivedi et al., “Challenges in core reactivity management and control optimization in physics design of Compact High Temperature Reactor”, *BARC Newsletter*, **317**, pp. 22-28, (2010)
5. D.K. Dwivedi and Anurag Gupta, “Development of adiabatic feedback model in 3D space-time analysis code ARCH”, *Life Cycle Reliability and Safety Engineering*, **4(4),** pp. 22-28, (2015)
6. Anurag Gupta, “ARCH- A 3-D core simulations code”, Proceedings of DAE-BRNS Symposium on “Advances in Reactor Physics (ARP-2017)”, 2017, Mumbai, India.
7. D.K. Dwivedi et al., “3D space time analysis of Anticipated Transient Without Scram in CHTR with Fuel Temperature feedback”, *Select Papers from ThEC15*. 10.1007/978-981-13-2658-5_31 (2019)
8. D.K. Dwivedi et al, “3D space-time analysis of ATWS in compact high temperature reactor with integrated thermal-hydraulic model in code ARCH-TH” *Annals of Nuclear Energy* **110**, 306–316 (2017)
9. K.K. Panda et al., “Numerical simulation of high temperature sodium heat pipe for passive heat removal in nuclear reactors”, *Nuclear Engineering and Design*, **323**, pp. 376-385, (2017)
10. A. Borgohain et al., “Natural circulation studies in a LBE loop for a wide range of temperature”, *Nuclear Engineering and Design*, **300**, pp. 358-375 (2016)
11. OECD/NEA Nuclear Science Committee, “Handbook on Lead-bismuth Eutectic Alloy and Lead Properties, Materials Compatibility, Thermal-hydraulics and Technologies”, 978-92-64-99002-9, (2007)
12. OECD/NEA, “Handbook on Lead-bismuth Eutectic Alloy and Lead Properties, Materials Compatibility, Thermal-hydraulics and Technologies”, No. 7268, (2015)